A Study of Sub-MMW Systems and Component requirements

H. Bruce Wallace
ORSA Corporation
mmw@orsacorp.com
Mark Rosker
DARPA/MTO
mrosker@darpa.mil

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Purpose of Study

- Assess system concepts that drive developers to the 100-500 GHz RF band.
- Evaluate key issues by successfully demonstrating, through analysis, the system concepts
- Define requirements for components to make these system concepts realizable.

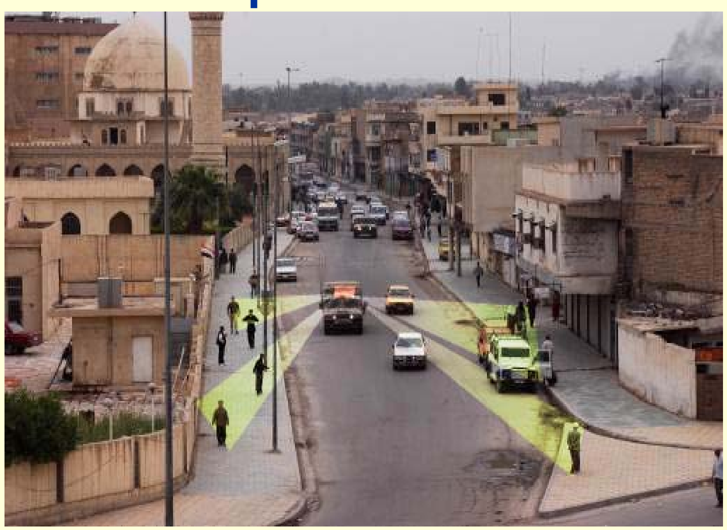
Three system concepts were identified that require a significant component development effort above 100 GHz

Sub-MMW Sensor Applications That Cannot Be Done Any Other Way

All-Weather Terrain Avoidance*

*** radome-limited aperture**

Concealed Weapons Detection at Range**



****at least 100m**

All-Weather Look-Down† ISR

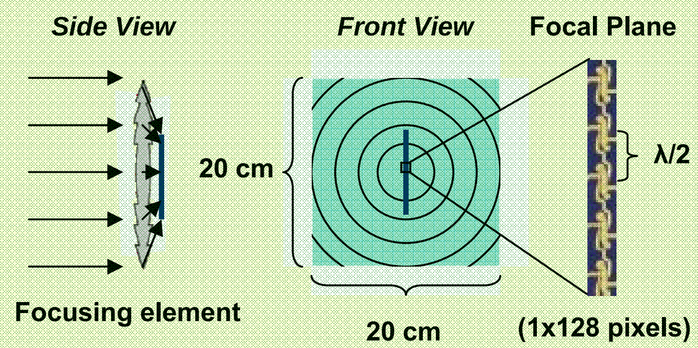
Most stressing component requirements

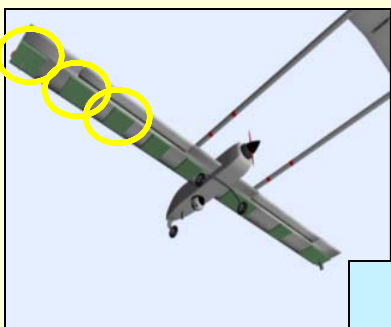
† scan angles > 60°

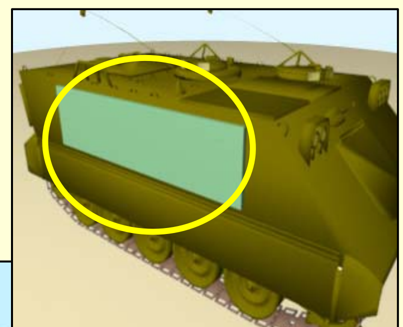
A common sub-aperture at 340GHz will provide the building block for these imaging applications

SWIFT Objective and Impact

SWIFT Sub-Aperture Objective Demo







Program Objective

- **Develop a <u>sub-aperture</u> transceiver to enable imaging at sub-MMW frequencies**

Impact

- **Look-down ISR into urban canyons**
- **All-weather obstacle avoidance**
- **Concealed weapons detection beyond the blast range**

SWIFT will drive development of extremely high speed <u>electronics</u> "World's Fastest Transistors / MMICs"

Questions to be Examined

- What is the optimum frequency?

  This depends on:

  - Resolution requirements and antenna restrictions
  - Atmospheric effects
  - If the system is passive, the sky temperature
  - Material properties
- What source power is required?
- What system noise figure is required?
- What type of architecture will be required to provide "video" frame rate imaging?
- What type of commonality can be developed to solve multiple needs?

Human Eyeball Resolution

The starting point for resolution will be "See" as well as the human eye. A search on the Internet, a various text books results in different answers.

Starting with Skolnick and Jenkins and White: The pupil can change size from 2 to 8 mm, depending on the brightness and age of the individual. For this exercise we assume a pupil of 5 mm.

$D_{iris} := .005 \cdot m$ $\lambda := 0.55 \cdot 10^{-6} \cdot m$ $\theta eye_0 := 1.22 \cdot \frac{\lambda}{D_{iris}}$ $\theta eye_0 = 1.342 \times 10^{-4}$

From Clarke(Clarkvision.com: 0.3 arc-min): $\theta eye_1 := 0.3 \cdot 2.91 \cdot 10^{-4}$

From W.J.Donnelly and A. Roorda,: "Optical pupil size in the human eye for axial resolution," J. Opt. Soc.Am. A, Vol. 20, No. 11, Nov. 2003 $\theta eye_2 := 4.5 \cdot 10^{-4}$

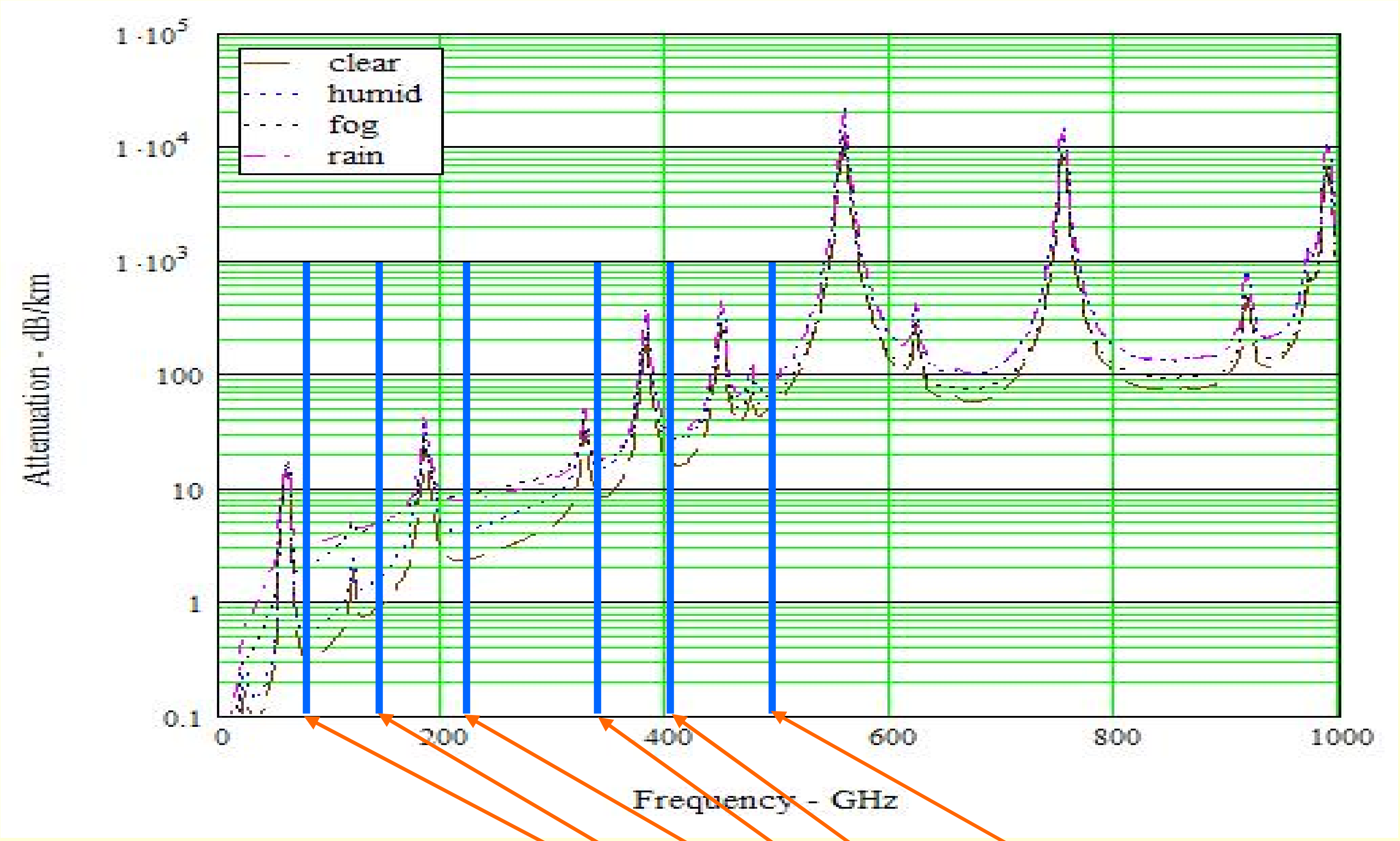
From Popa (Internet:1 minute of arc): $\theta eye_3 := 2.91 \cdot 10^{-4}$

The paper by Donnelly demonstrates that the eye is far from be diffraction limited. For this exercise, I am going to choose a resolution that is twice the diffraction limited value which is also close to that of Popa.

$$\theta eye = \begin{pmatrix} 1.342 \times 10^{-4} \\ 8.73 \times 10^{-5} \\ 4.5 \times 10^{-4} \\ 2.91 \times 10^{-4} \end{pmatrix}$$

$\theta eye_{3dB} = 2.684 \times 10^{-4}$

The Atmosphere and Frequencies of Interest



For the first part of the study, only 95,140,220,340,410, and 500 GHz were selected

Basic System Characteristics

- Defining the basic system parameters for the system.
  - NF is based on published data
  - Antenna loss of 3 dB for lack on anything else

$$F_{req} := \begin{pmatrix} 95 \cdot 10^9 \\ 140 \cdot 10^9 \\ 220 \cdot 10^9 \\ 340 \cdot 10^9 \\ 410 \cdot 10^9 \\ 500 \cdot 10^9 \end{pmatrix} \cdot Hz \qquad NF := \begin{pmatrix} 2 \\ 4 \\ 9 \\ 11 \\ 12 \\ 12 \end{pmatrix} \qquad L_{ant} := \begin{pmatrix} 2 \\ 2 \\ 2 \\ 2 \\ 2 \\ 2 \end{pmatrix}$$

- The “required” antenna sizes for eyeball resolution become:

$$D_{ia} = \begin{pmatrix} 14.344 \\ 9.734 \\ 6.194 \\ 4.008 \\ 3.324 \\ 2.725 \end{pmatrix} m$$

These antenna dimensions imply that some form of array processing will be required

Selected Atmospheric Conditions

- Clear atmosphere with sky condition 3 (4.67 g/m^3)
- Humid with sky condition 4 (12.8 g/m^3)
- Fog + humid with sky condition 4
- Rain + humid with sky condition 5

It is also assumed the atmospheric particulates do not change the sky temperature. Fog is also considered to be 0.3 km deep.

We therefore have to redefine the sky temperatures and atmospheric attenuations

$$SKY = \begin{pmatrix} 60.374 & 106.162 & 106.162 & 238.58 \\ 114.121 & 171.423 & 171.423 & 268.953 \\ 212.599 & 254.973 & 254.973 & 280.197 \\ 274.137 & 282.114 & 282.114 & 282.972 \\ 274.137 & 282.114 & 282.114 & 282.972 \\ 274.137 & 282.114 & 282.114 & 282.972 \end{pmatrix} K$$

$$ATT := \begin{pmatrix} .015 & .35 & .71 & 2.15 \\ .093 & .7 & 1.39 & 3.3 \\ .259 & 2 & 2.9 & 4.6 \\ 2.48 & 9.5 & 10.58 & 12 \\ 6.06 & 15 & 16.2 & 17.5 \\ 26.5 & 50 & 51.5 & 52.5 \end{pmatrix} \bullet km^{-1}$$

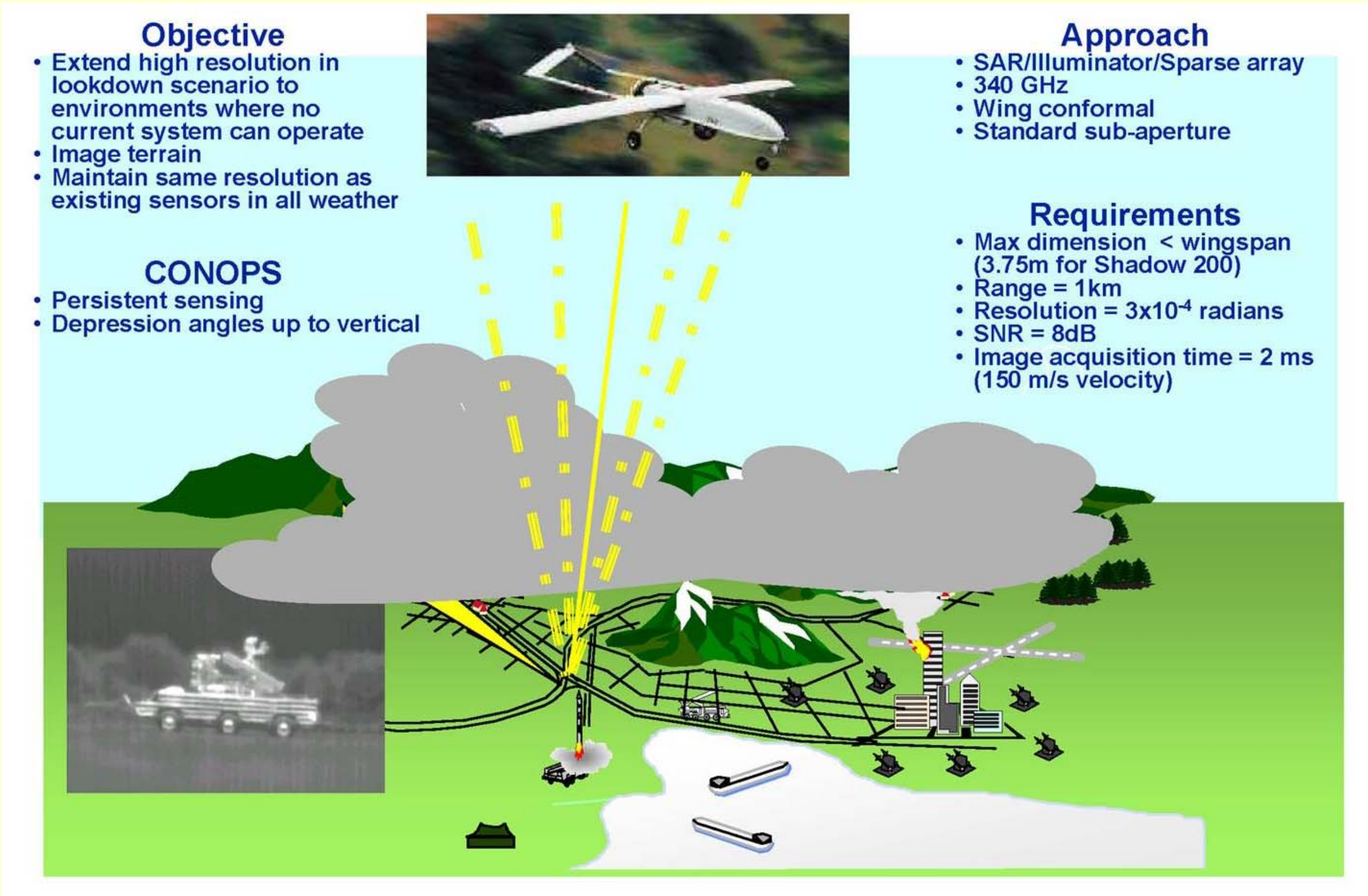
Background Emissivities

Typical emissivities in the EHF are (from Wikner, USARL):

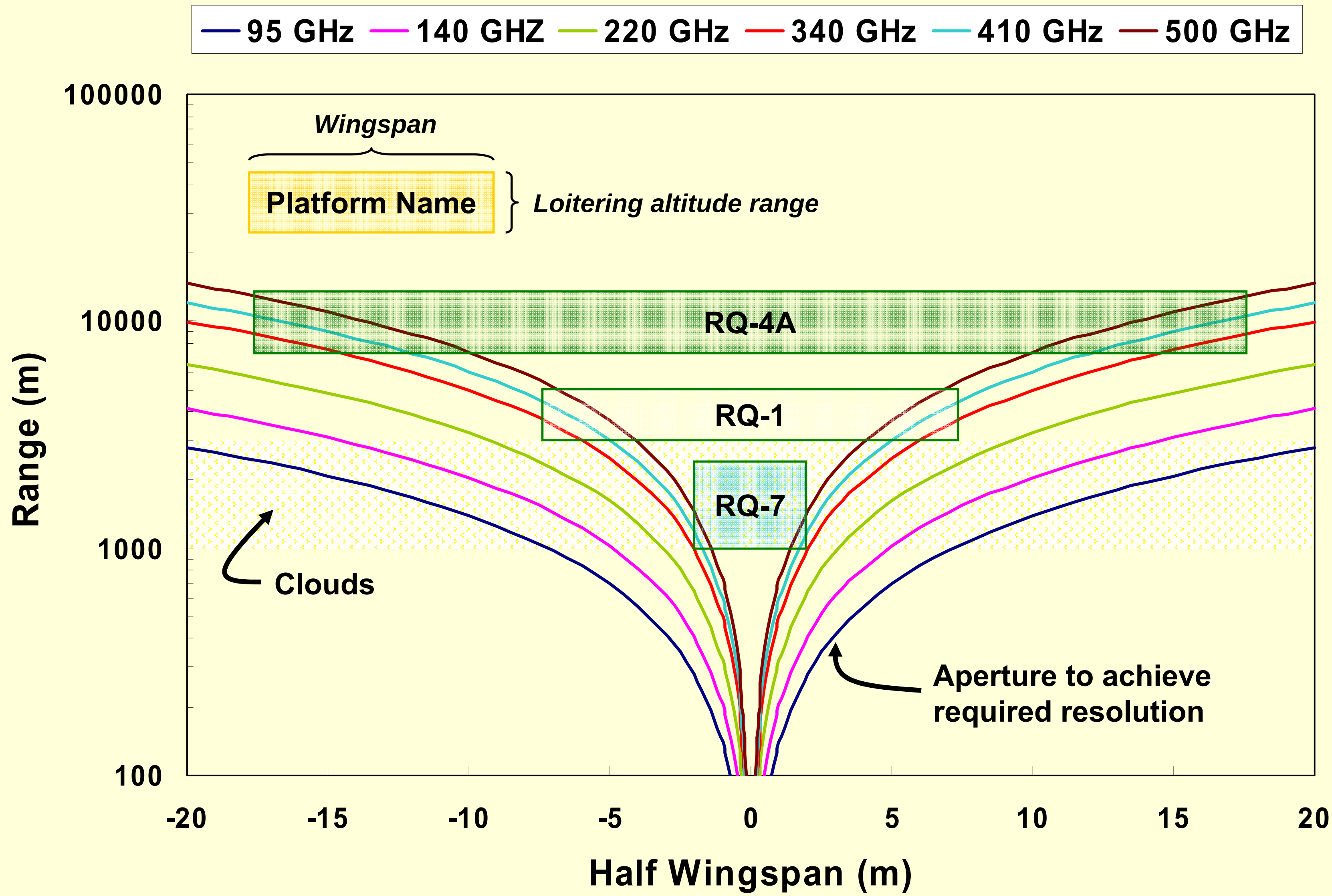
- Clean Metal = 0
- Concrete = .905
- Asphalt = .914
- Gravel = .921
- Water = 0.5
- Dirt = 1.0
- Deciduous Trees = .95
- Coniferous trees = 1.0
- Wet concrete/asphalt = 0.8
- Wet dirt 0.9
- Wet metal = 0.25
- Snow = 0.7 (depending on depth)
- Wood = 0.95 (depending on thickness)
- Grass = 0.95 (depending on height)

For this study these values were assumed to be constant through 500 GHz. This assumption is not strictly correct for dielectrics, and is also a function of the relative surface roughness and scattering angle.

UAV Based Look Down Sensor



Platform Wingspan and Resolution



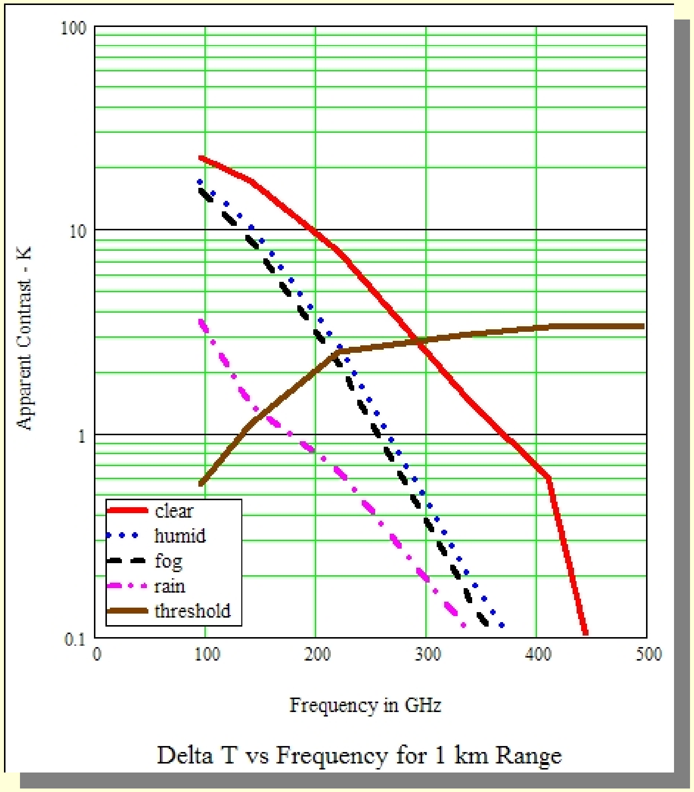
UAV Passive Imager Performance

Contrast of a fully filled pixel

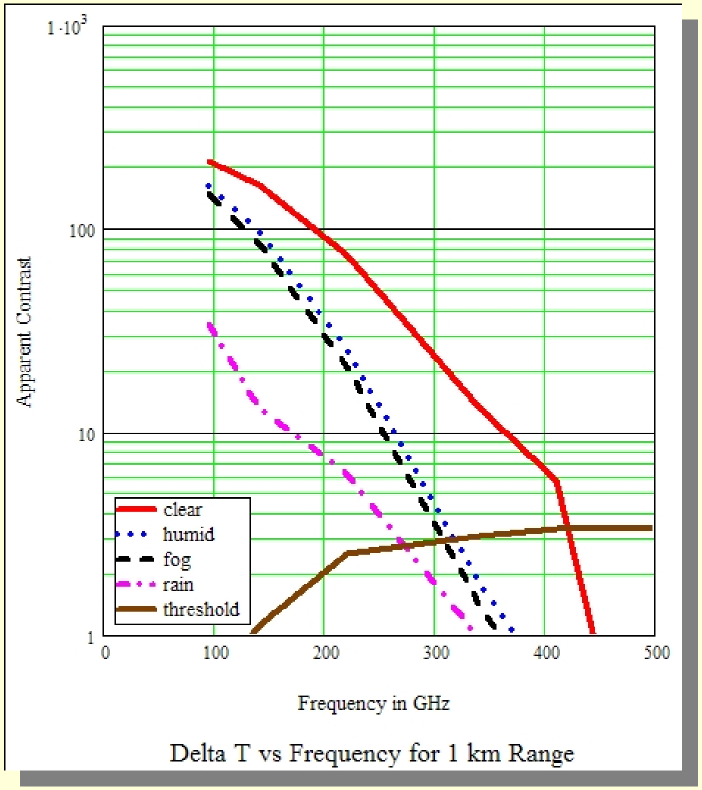
System NEDT:

$$\Delta T = \begin{pmatrix} 0.093 \\ 0.186 \\ 0.418 \\ 0.511 \\ 0.558 \\ 0.558 \end{pmatrix} K$$

Threshold= 6 X NEDT



10% Emissivity

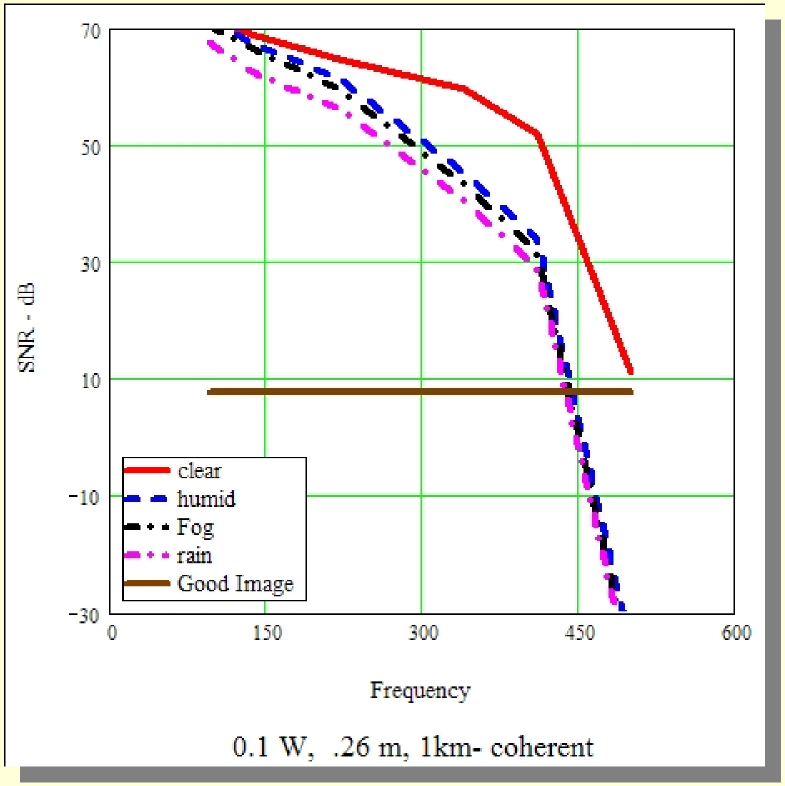


Metal Target

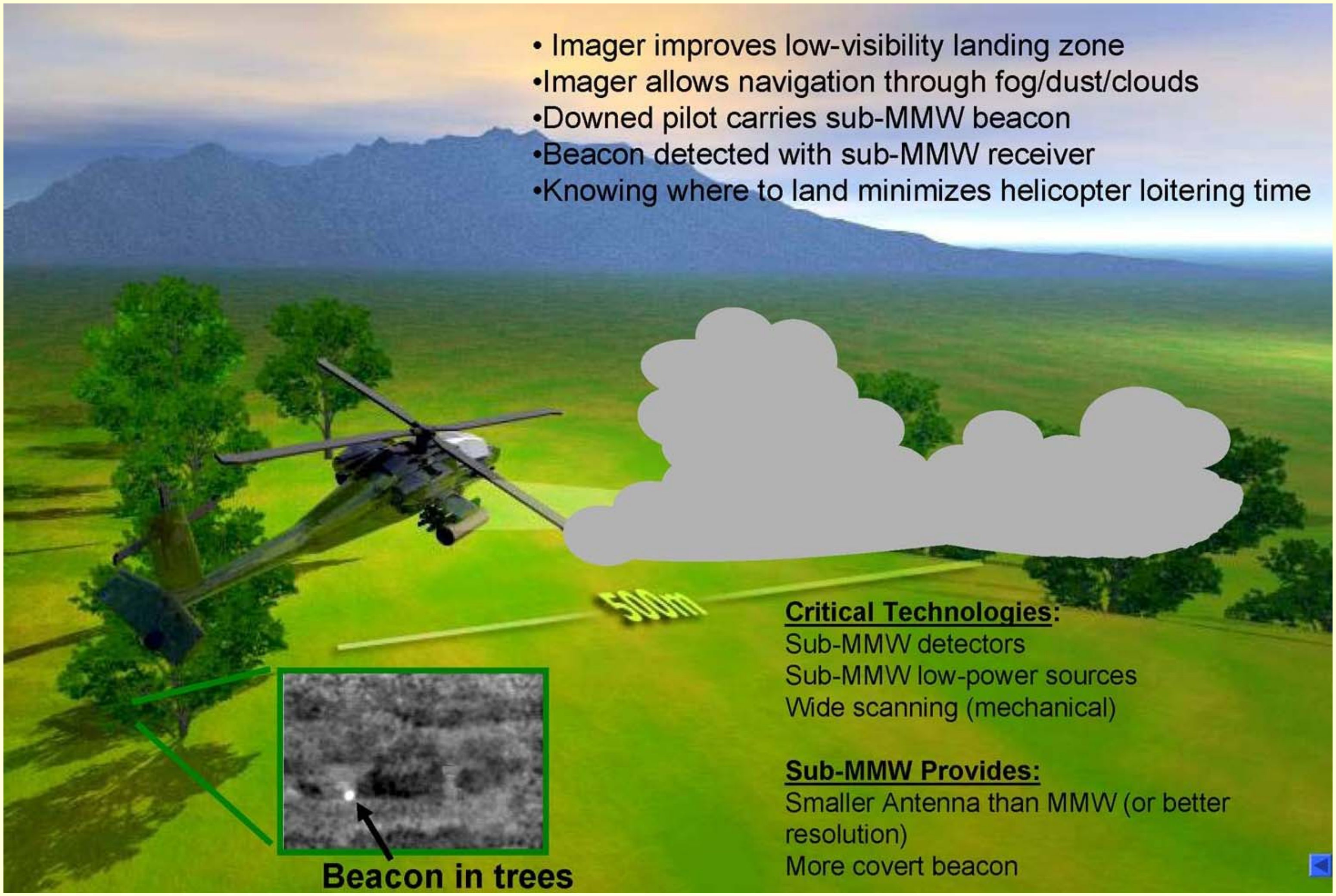
In bad weather, passive operation will not provide sufficient contrast for mapping if the desired resolution is maintained

Active System using Coherent Processing and Array Beamforming

- This chart is for a 0.26m sub-aperture that may be integrated into a wing borne array
- Total power requirement will be based on required Field of Regard (FOR)
- Coherent processing will be used to perform array processing along the wing and SAR processing along the flight path.
- To cover a FOR of +-20 deg from the vertical, a 128x1 pixel FPA would be required for each sub-aperture
- There is also sufficient SNR to allow thinning the wing array



Terrain Avoidance



Terrain Avoidance

We will set the required resolution to 1 meter and for this application we will set the max range at 500 meters as the aviation community has suggested that the minimum required range for obstacle avoidance for helicopters is 400 meters.

Define antenna sizes:

$$\text{range} := .5 \cdot \text{km}$$

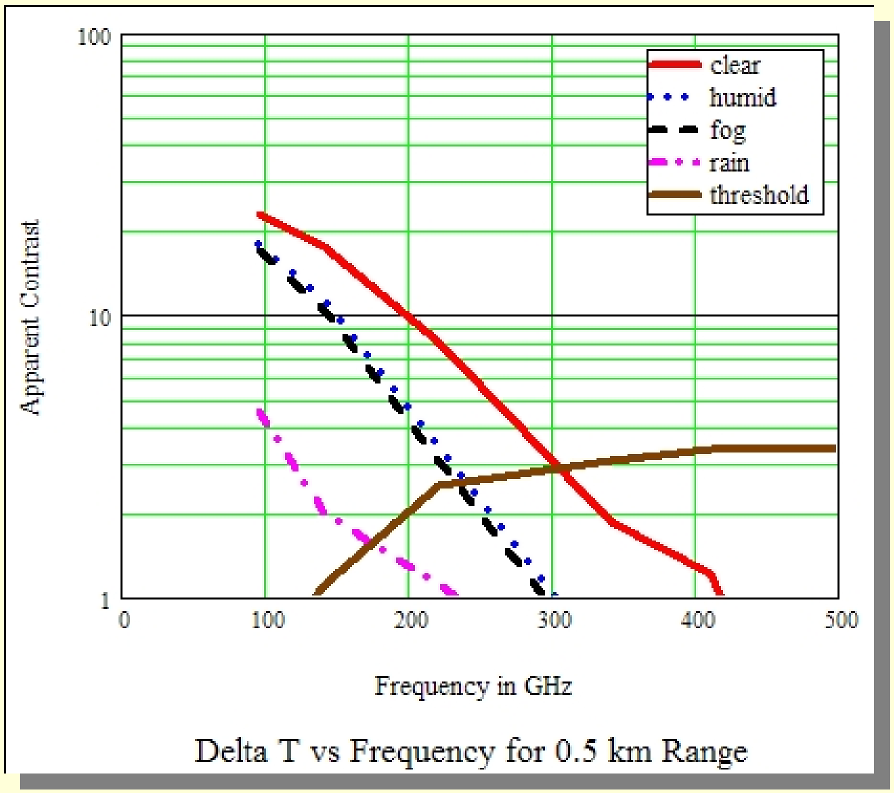
$$D_{ia_f} := 1.22 \cdot \frac{c}{F_{req_f} \cdot \left(\frac{1 \cdot m}{\text{range}}\right)}$$

$$D_{ia} = \begin{pmatrix} 1.926 \\ 1.307 \\ 0.832 \\ 0.538 \\ 0.446 \\ 0.366 \end{pmatrix} m$$

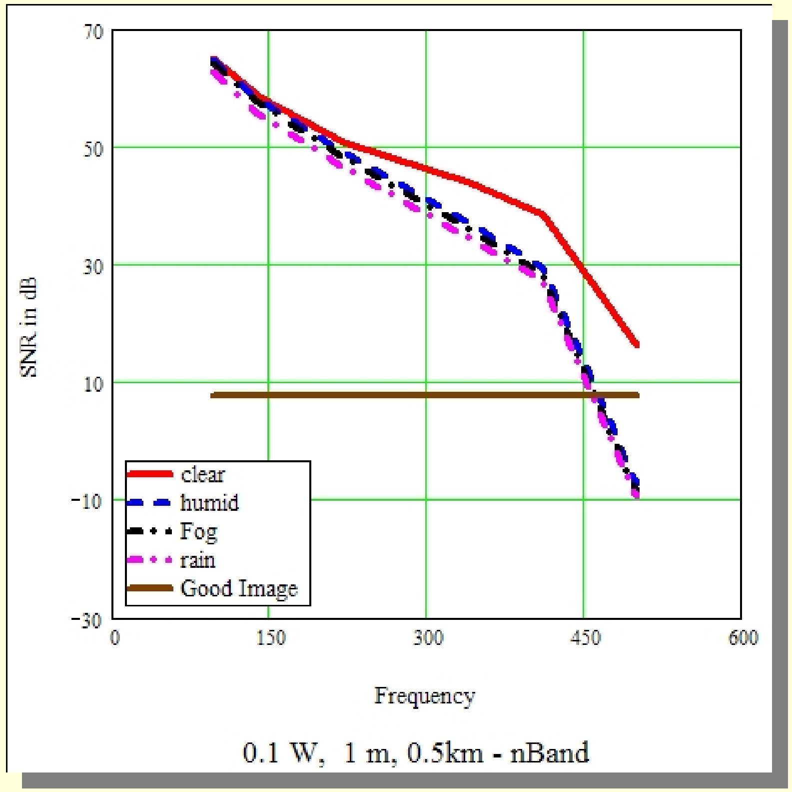
The antenna sizes for this resolution are becoming reasonable and provide some room for system trades. The following curves were generated for a 1 meter aperture

System Performance for both Passive and Non-coherent Active Modes

σ_0 = -20 dB   Transmit Power/Pixel = 0.1 W



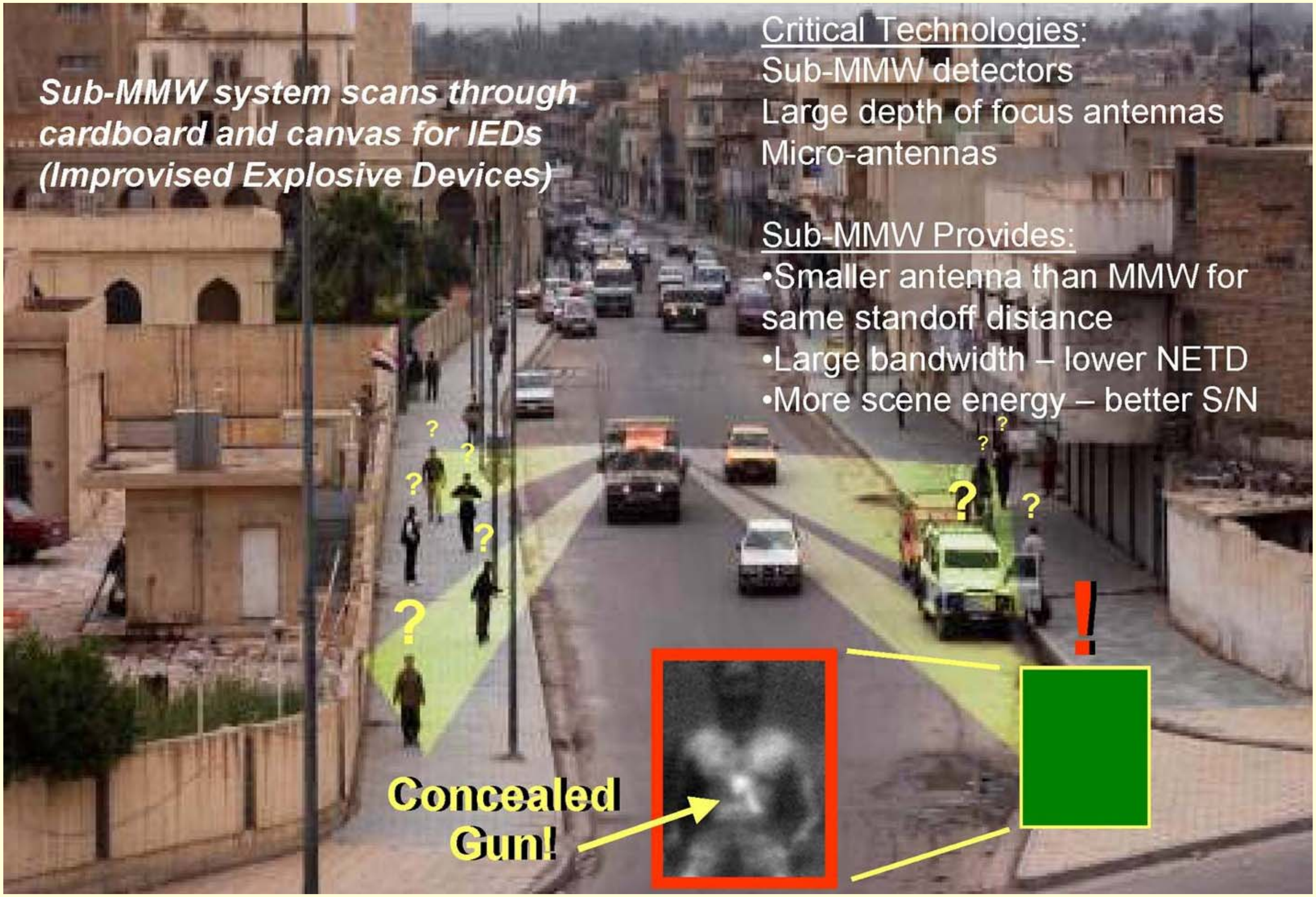
Passive – 10% Emissivity Variation



Active – narrow band Non-coherent

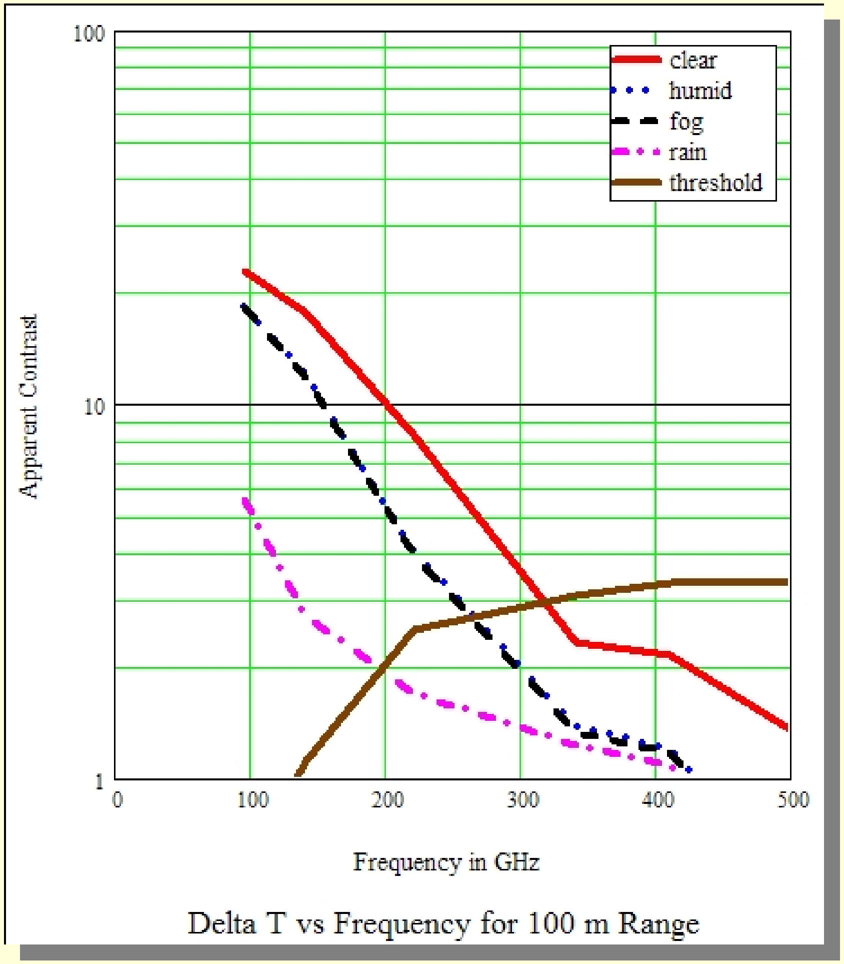
Passive performance is inadequate while active non-coherent offers sufficient SNR at 500m for a narrow Field of Regard. For large Field of Regard, either more transmitter power will be needed or coherent processing

Weapons Detection



Performance

- Only passive sensing was examined for this application
- This chart uses the sky as the illumination function
- While the trends are the same as previously, the attenuation is not quite as severe.
- Eyeball resolution is assumed.
- The NEΔT is assumed as previously for this curve
- Bandwidth is 5 GHz at all frequencies



Delta T vs Frequency for 100 m Range

Model of Concealed Weapon

$$\mathbf{T_{matill} = T_{mat} * \varepsilon_{mat} + T_{ill} * L_{mat}}$$

where

ε_{mat} = the emissivity of the material = 1-Lmat
T_{mat} = the material physical temperature
T_{ill} = the apparent temperature illuminating the out side of the material
L_{mat} = the loss in the material

The apparent temperature (under the material) of the weapon would then be:

$$\mathbf{T_{gun} = \varepsilon_{weap} * T_{weap} + \rho_{weap} * T_{matill}}$$

and since $\varepsilon = 1 - \rho$

$$\mathbf{T_{gun} = \varepsilon_{weap} * T_{weap} + T_{matill}(1 - \varepsilon_{weap})}$$

where

ε_{weap} = the emissivity of the weapon
T_{weap} = the weapon physical temperature

Then looking back through the material at the weapon would yield:

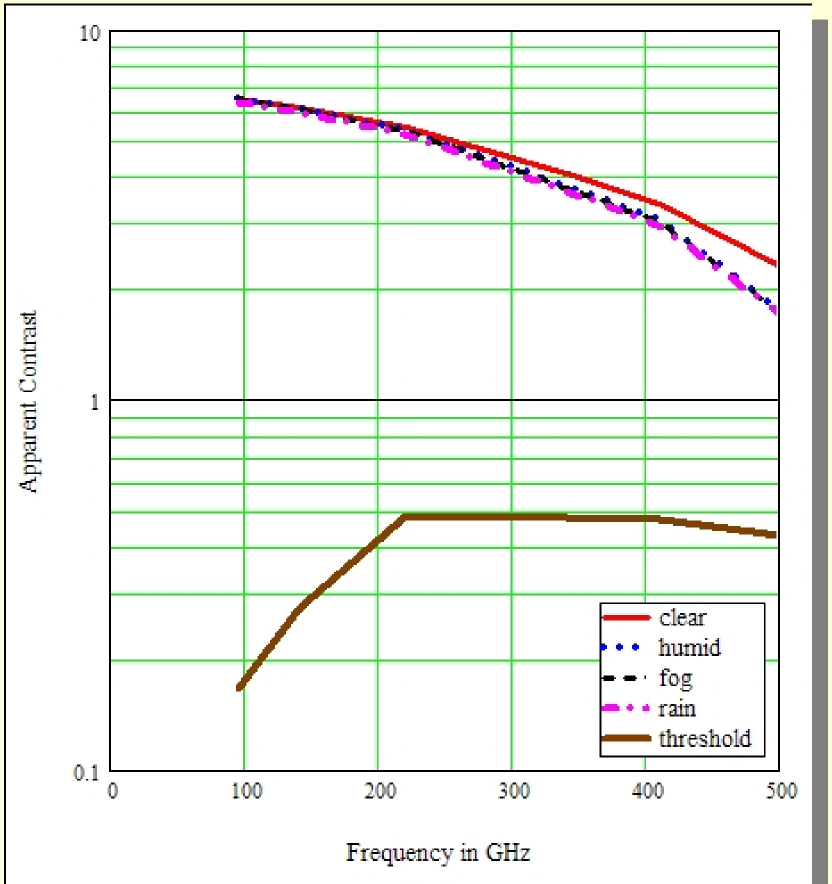
$$\mathbf{T_{appgun} = (L_{mat} * T_{gun} + (1 - L_{mat}) * T_{mat}) * (1 - \rho_{mat}) + \rho_{mat} * T_{ill}}$$

where the third term is the reflection off of the surface of the material.

Performance vs. Modeled Concealed Weapon

- Material Losses are from E. Brown, UCSB.
- Skin emissivities are from QinetiQ
- Ambient Temperature=289K
- Clothing Temperature=294K
- Weapon Temperature=299K
- Body Temperature=304K
- Bandwidth = 5%
- NF = 8dB
- Threshold = 3:1
- Frame rate = 10Hz

$$L_{mat} = \begin{pmatrix} 0.804 \\ 0.724 \\ 0.603 \\ 0.457 \\ 0.389 \\ 0.316 \end{pmatrix} \qquad \varepsilon_{skin} = \begin{pmatrix} 0.644 \\ 0.69 \\ 0.768 \\ 0.822 \\ 0.855 \\ 0.92 \end{pmatrix}$$



Delta T vs Frequency for 50 m Range

Trade space for weapons detection looks large enough to investigate phenomenology and components in more detail

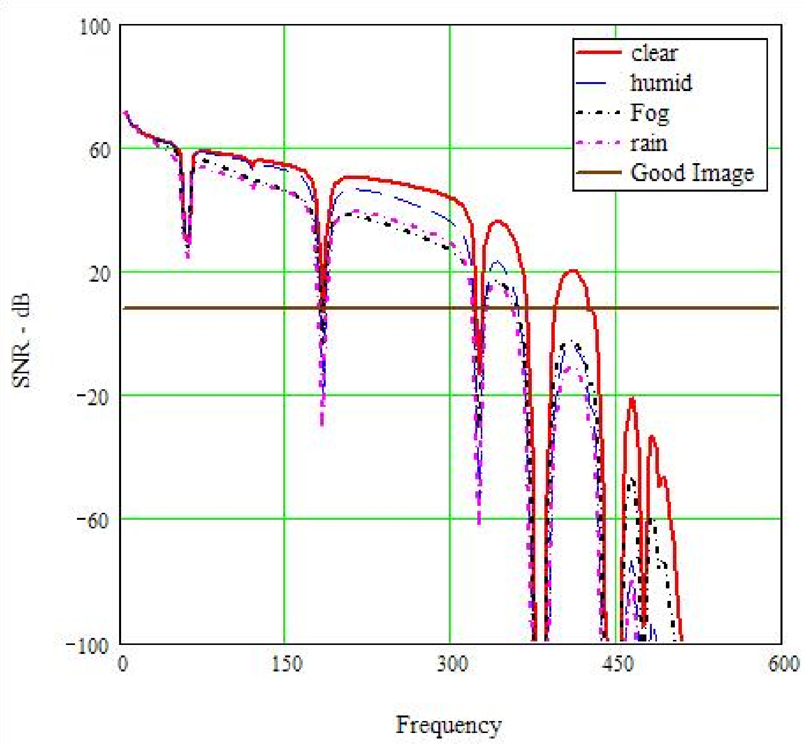
Selected Sub-Aperture Characteristics

These characteristics differ from those used in the previous work but were selected to balance requirements

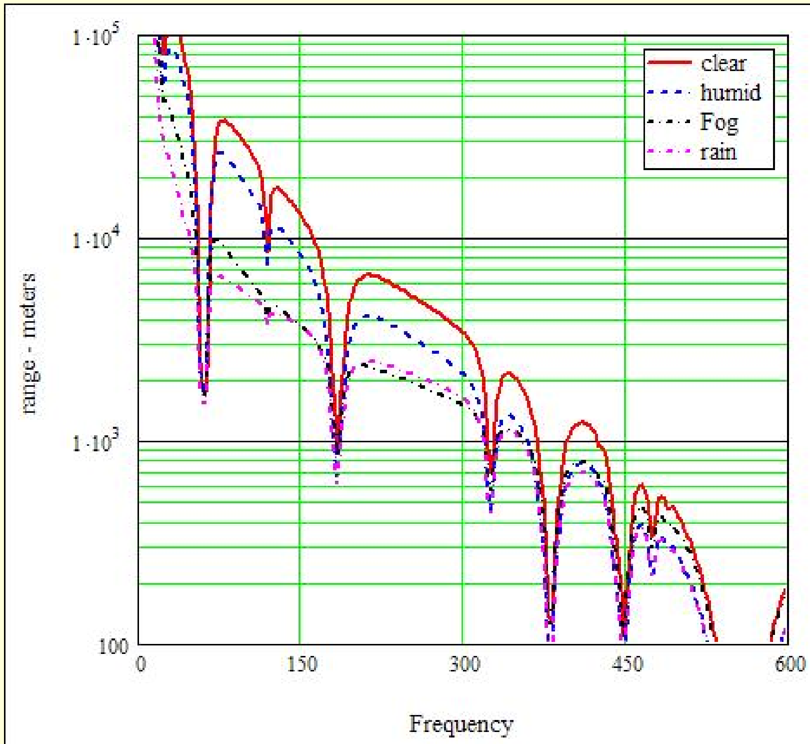
- Coherent transmitters and receivers
- 1 Watt total transmitter power defined by UAV
- 40 deg Field of Regard (FOR) in azimuth defined by UAV and Terrain Avoidance
- 10 deg FOR in elevation defined by Terrain Avoidance
- 8 dB noise figure defined by Weapons Detection
- 5% RF Receiver Bandwidth defined Weapons Detection
- <1% transmitter bandwidth defined by UAV and TA
- Pixel output time constant = 1/30 sec
- 33x136 Focal Plane
- Sub-aperture antenna size = 0.2 m defined by required near-field of 100m

This sub-aperture can be used as a building block for all three systems

SNR and Range Performance of the UAV Look Down Sensor



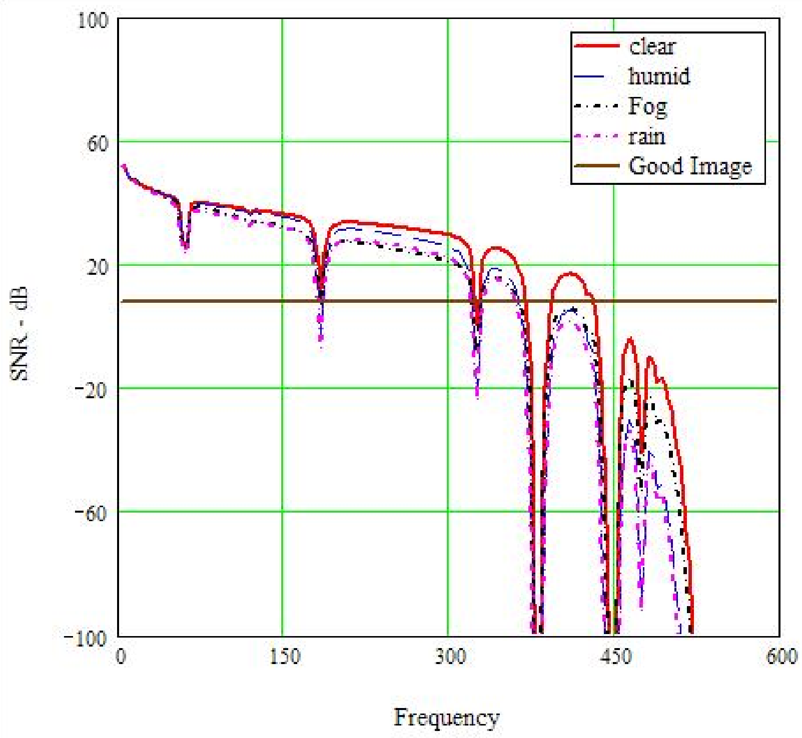
1.0 W, .2 m, 1km- coherent



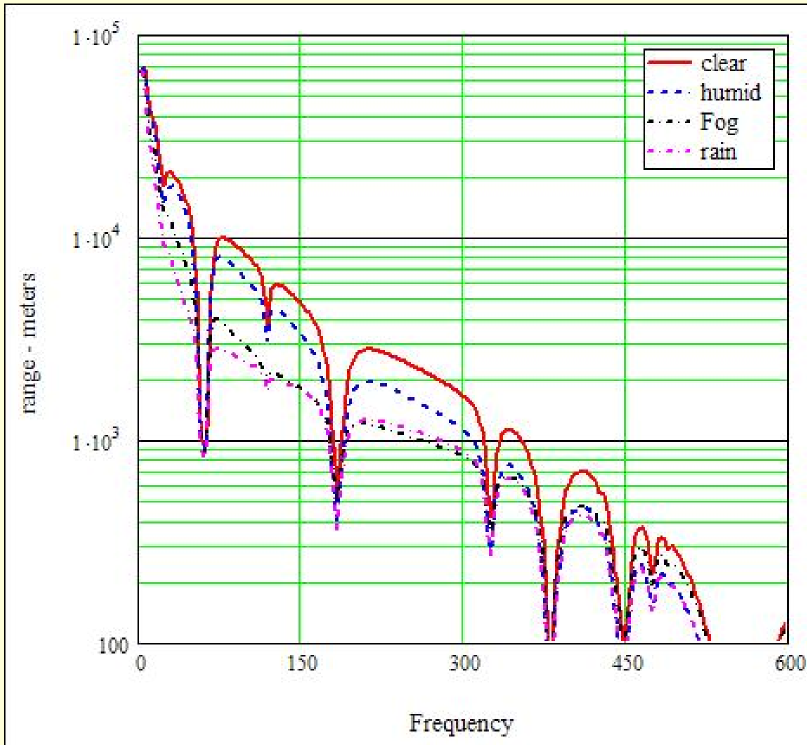
1.0 W, sparse SAR, 8dB SNR

The sparse array results were calculated with 50% thinning

SNR and Range Performance of the Terrain Avoidance System



1.0 W, .2 m, 1km- coherent

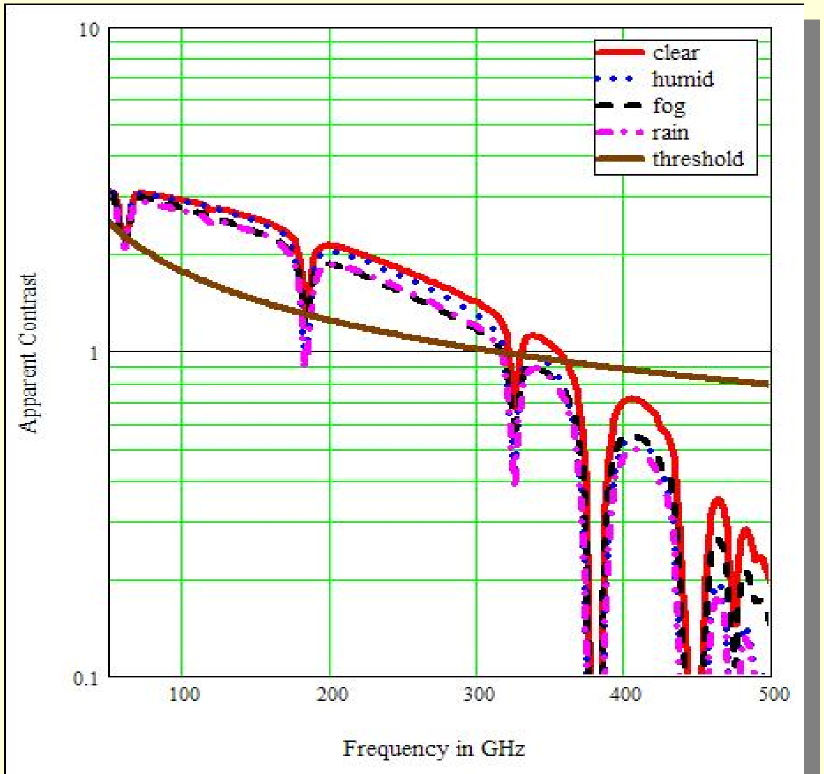


1.0 W, .2m, 8dB SNR

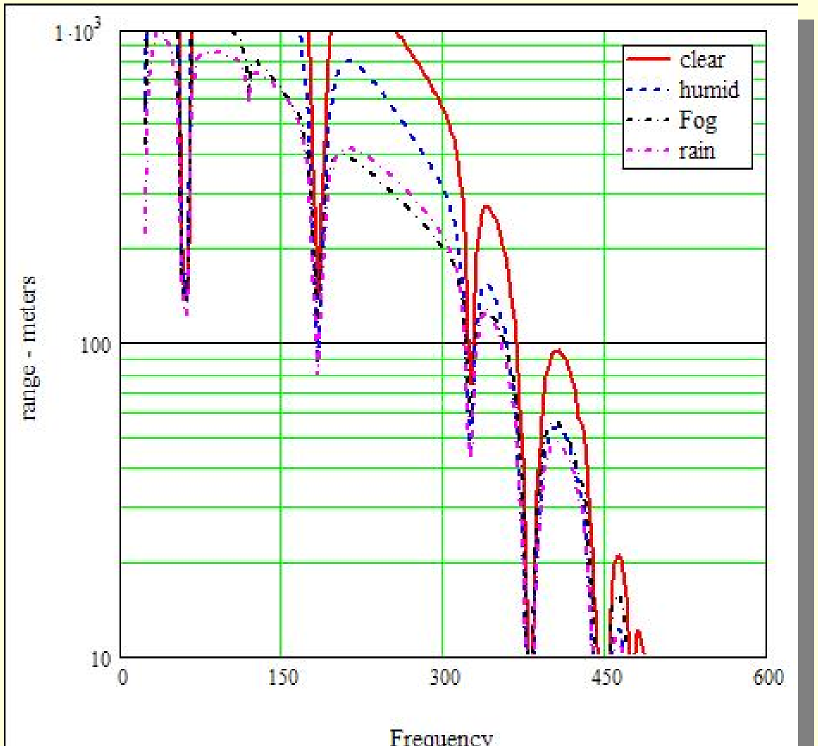
Performance exceeds proposed requirements

SNR and Range performance of the Passive Weapons Detection System

Target is a metal weapon under two layers of wool clothing - 17C environment



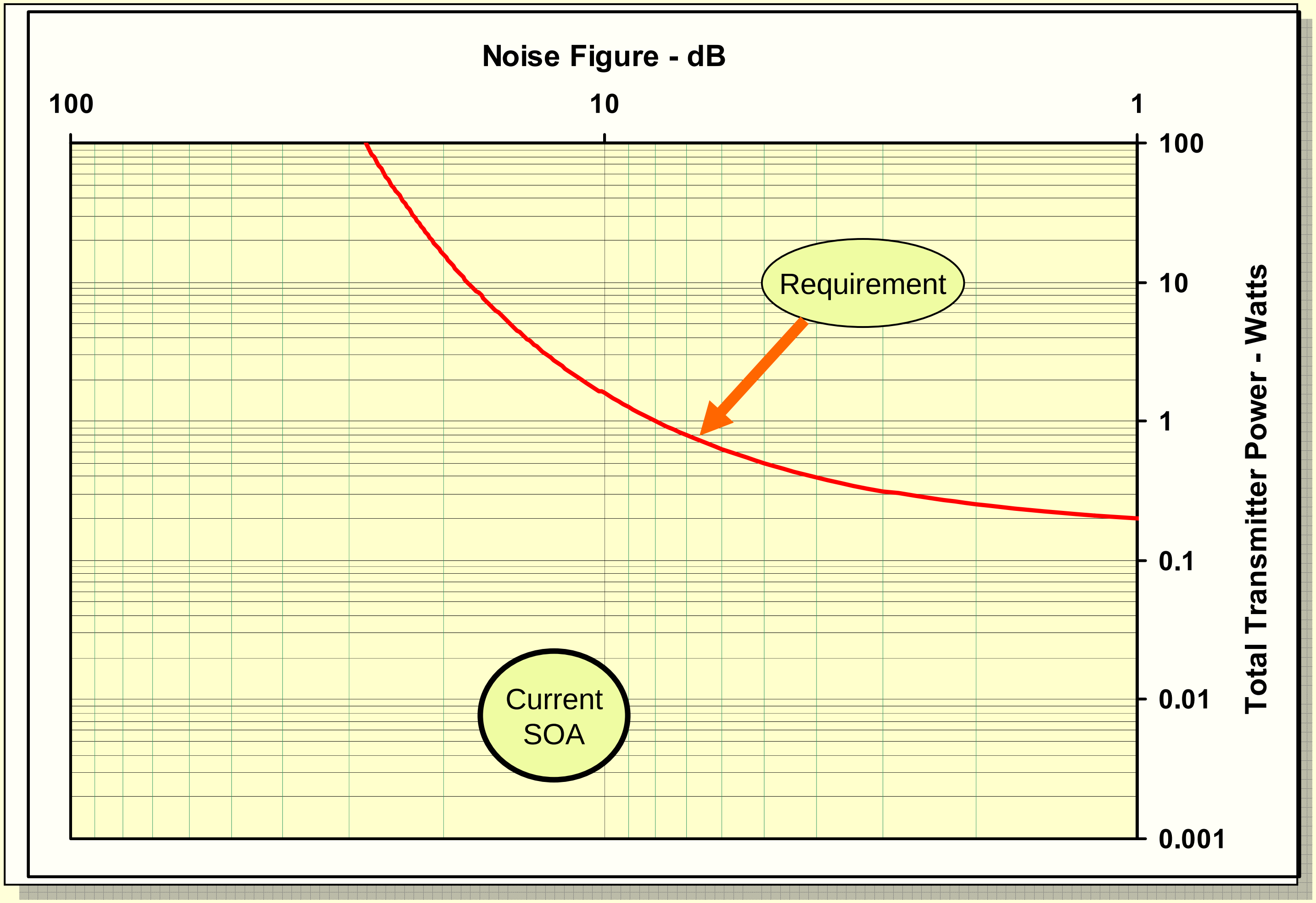
Delta T vs Frequency for 100 m Range



Range for 5:1 contrast

Under these conditions performance is very close to proposed requirements

Program Requirements vs the State-of-the-Art



Summary

- Three military applications were investigated that require the development of sub-millimeter wave technology
- A development of a single sub-aperture will allow forming arrays for each application
- Development of receivers with Noise Figures of 8 dB and Transmitters concepts with total power levels of 1 W would enable the concepts

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H. Bruce Wallace
ORSA Corporation
1003 Old Philadelphia Road
Aberdeen, MD 21001
USA

mmw@orsacorp.com

Mark Rosker
DARPA/MTO

mrosker@darpa.mil

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